

Safety Guide 100

DESIGN AND DEVELOPMENT GUIDE FOR NNSA TYPE B PACKAGES

CHAPTER 9

MATERIALS AND FABRICATION

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CHAPTER 9.0

MATERIALS AND FABRICATION

9.1 INTRODUCTION

This chapter discusses materials and fabrication methods that have been successfully used in the development of packages to transport special assemblies, components, and radioactive material associated with the nuclear explosives and weapons safety program for NNSA.

9.1.1 Purpose and Scope

The information in this chapter is intended to aid the packaging developer in selecting materials and fabrication methods for packaging. Materials are selected for their ability to satisfy the structural, thermal, subcriticality, shielding, and compatibility requirements. The availability and cost of materials must also be considered.

The selection of fabrication methods will be based on the methods that will produce the desired component (using the selected materials) at a reasonable cost. The availability of fabrication equipment and the properties of the fabricated components must also be considered.

9.1.2 Material Selection Process

Packaging materials are selected based on the package content material and the package safety functions required to transport this material. Materials typically packaged in NNSA packages are given in Table 9-1.

The materials used in NNSA packages must enable the package to satisfy the following safety functions: contain the radioactive material; provide shielding from radiation, and maintain subcriticality. The packaging must also keep the contents in place (confinement). These functions, in part, are accomplished by designing structural integrity into the packaging as well as designing the package to accommodate the thermal loads which may be experienced by the packaging. The following paragraphs discuss the material characteristics needed to accomplish each of these functions.

Table 9-1. Typical NNSA Package Content Materials

Material	Form	Source of Nuclear and Physical Properties
^{233}U , ^{234}U , ^{235}U , ^{236}U , ^{238}U	solid (parts, powder, chips, etc.): pure metal, oxides, nitrides, other compounds	SCALE:A Modular Code for Performing Standardized computer Analyses for Licensing Evaluation, NUREG/CR-0200, Rev. 7, 2004
^{238}Pu , ^{239}Pu , ^{240}Pu	solid (parts, powder, chips, etc.): pure metal, oxides, nitrides, other compounds	SCALE:A Modular Code for Performing Standardized computer Analyses for Licensing Evaluation, NUREG/CR-0200, Rev. 7, 2004
Tritium	Solid, liquid, or gas (mixtures and compounds)	Health Physics Manual of Good Practices for Tritium Facilities, MLM-3719, Draft EG&G Mound Applied Technologies, December 1991

A sample packaging showing the function(s) of each of the components and possible materials for those components is shown in Figure 9-1.

Containment. The containment boundary must prevent the release of radioactive materials during both normal conditions of transport (NCT) and hypothetical accident conditions (HACs) as stipulated in the regulations. The walls, heads, welds, fasteners, and seals that make up the containment boundary must be capable of withstanding the mechanical, thermal, and physical conditions to which they may be subjected.

Shielding. The radiation dose rate must not exceed regulatory limits during use. For NCT, the regulations stipulate dose rates at the surface of the package and at 1 m from the package surface; whereas for HAC only dose rates at 1 m from the package surface are specified. If the packaging is deformed during HAC, consideration must be given to the possibility that the radiation source may be nearer to the surface of the packaging and, consequently, the radiation dose rate at 1 m may be higher after deformation. In some cases, packaging design features that satisfy functions other than shielding also provide some shielding. In other cases, the materials used or the thicknesses of the materials used will have to be changed to provide adequate shielding. In addition to transportation, the packaging may be required to meet more stringent facility dose rates. These lower criteria must be considered during the material and fabrication selection process.

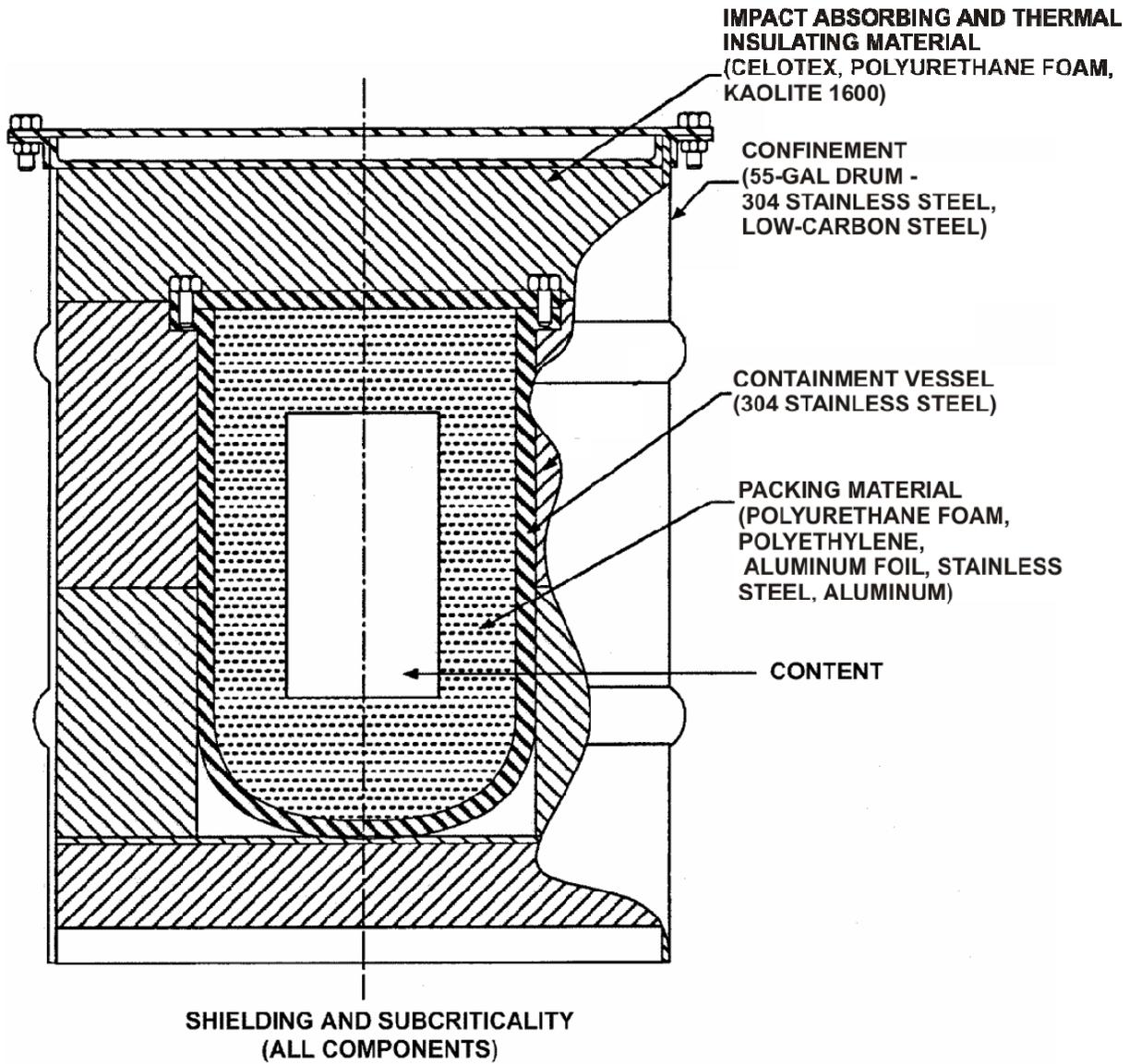


Figure 9-1. Sample Package.

Subcriticality. Subcriticality must be maintained during all NCT and HAC. In many cases, subcriticality is dependent on keeping moderating material (usually water) out of the containment boundary, (e. g., the containment vessel) and on maintaining adequate spacing between multiple containers. With the advent of the crush test, possible reduced spacing of post-HAC units must also be considered.

Structural Integrity. Structural integrity is often supplied by impact limiters. The components of the packaging that act as an impact limiter are usually those components at or near the outer surface of the packaging. The impact limiters absorb energy from the HAC drops and crush tests such that the other functions of the packaging are preserved.

Thermal. The characteristics of the materials used must accommodate the thermal loads that may be applied to the package. Thermal loads include radioactive decay heat from the contents, heating from the sun (insolation), and heat from a HAC thermal event. The environment can also affect the thermal load on the package. Various combinations of thermal loading can occur during the shipment of a package. The thermal properties of the materials used and the configuration of those materials must be such that containment, shielding, and subcriticality are maintained.

Confinement. The components of the packaging that provide confinement must hold the package together during HAC to the extent that the other functions of the packaging are maintained. Usually, the confinement components are those that make up the outer surface of the packaging. In the sample packaging (Figure 9-1), the confinement boundary consists of the stainless steel drum and drum lid. After the drop-test and crush-test portions of the HAC, the extent of the deformation and opening of the drum (i.e., the deformation of the confinement components) must be such that allowable radiation doses are not exceeded and containment is maintained during the fire test.

Packing Material. Packing material may be used inside the containment vessel and holds the contents in place. It may also enhance the structural integrity and thermal capabilities of the package, as well as provide confinement.

No single material can accomplish all of these functions; however, some materials contribute to more than one function. Materials should also be durable, easy to work with, and cost effective. Materials which have been successfully used for various functions and components are listed in Table 9-2. Materials other than these may be used in NNSA packagings; however, justification for their use must be documented.

Table 9-2. Packaging Materials and Their Functions

Material	Function						
	Containment	Shielding	Subcriticality	Structural Integrity	Thermal	Confinement	Packing Material
Austenitic stainless steel	x	x	x	x		x	x
Carbon steel	x	x		x		x	
High-strength steel	x					x	x
Aluminum alloy 6061	x					x	x
Cellulosic insulating board				x	x		
Inorganic refractory				x	x		
Ceramic fiber materials				x	x		
Fir plywood				x	x		
Redwood				x	x		
Urethane foam				x	x		x
Silicone foam							x
Ethylene propylene	x						

9.2 PACKAGING MATERIALS PROPERTIES

This section discusses the properties of individual materials that have been successfully used in NNSA packages.

9.2.1 Austenitic Stainless Steel

The most common austenitic stainless steels are from the Type 304/304L and Type 316/316L families of alloys. These alloys have excellent general corrosion resistance, ease of fabrication (including forming and welding), good combinations of strength and

toughness, oxidation resistance, availability of standards and specifications, and is available in a wide variety of shapes and sizes. Type 304L is an austenitic iron-base alloy nominally containing 18% chromium, 8% nickel, and a carefully controlled (0.03% maximum) carbon content. The "L" designation distinguishes the low-carbon grade from the nominal carbon content grade of 304 (that may contain up to 0.08% carbon). Types 316 and 316L stainless steel are similar to 304 and 304L in composition except that the 316s include an added 2% molybdenum. The addition of molybdenum enhances localized corrosion resistance in many aqueous media but, depending on product form, may add considerable expense compared with 304/304L alloys. The cast equivalents for these materials are CF-3 (304L), CF-8 (304), CF-3M (316L), and CF-8M (316). The cast materials do not have exactly the same composition as their wrought counterparts and typically have a duplex structure (ferrite in an austenite matrix) as opposed to a fully austenitic structure. None of these stainless steel alloys can be hardened by heat treatment, but each work hardens readily.

Based on composition specifications and the allowable ranges for all alloying elements, the only difference between Types 304 and 304L and between Types 316 and 316L is the carbon content. The small difference in carbon content has a rather insignificant affect on most physical and mechanical properties, but it can have a profound influence on corrosion resistance in some environments. The reason is that welding thermal cycles or other heat treatments that include the 500 to 800 °C temperature range, even for relatively short durations, tend to precipitate chromium carbides on the alloy grain boundaries of these stainless steels. The formation of these carbides deplete the surrounding material of chromium and the alloy loses its "stainless" character on a local basis. As the alloy carbon content is lowered, the rate and amount of carbide precipitate forming in the 500 to 800 °C temperature range decreases. With less than 0.03% carbon, Types 304L and 316L have very good resistance to potential carbide precipitation problems.

Otherwise, the influence of carbon content on the properties and performance of these alloys is minor. For example, mechanical properties (tensile and yield strengths) of solution treated Types 304 and 304L are essentially identical (some sources indicate that Type 304 is a few percentage points stronger at low temperature, but the difference decreases rapidly as temperature is increased). Compared with Type 304, the lower carbon content of Type 304L improves significantly the notch toughness of welds (particularly at low/cryogenic temperature) and decreases work hardening somewhat. Creep resistance of Type 304 is somewhat higher than that of Type 304L under some

loading conditions. Physical properties of Types 304 and 304L, such as thermal conductivity and coefficient of expansion, are considered to be essentially identical.

The same trends between properties of Types 316 and 316L apply, and in general, there are no significant property differences between the Type 304 and the Type 316 alloy families. One notable exception is that compared with Types 304/304L, Types 316 and 316L are particularly prone to embrittlement during heat treatment or other thermal cycles that involve the temperature range of 650 to 850 °C. In addition to carbide precipitation, which occurs in this temperature range and was discussed earlier, sigma phase formation can be very detrimental to ductility and toughness. Sigma phase forms most readily from the ferrite phase (which is present in most welds of austenitic stainless steels) but forms very slowly at austenite grain boundaries, too. When molybdenum is present, as in Types 316/316L, the rate of sigma formation can be much more rapid at either location. A practical problem for container materials in this regard is the 30-minute 800 °C "thermal test" following drop tests. The possibility of embrittled welds of Types 316 or 316L is substantial after this heat treatment.

As a result of the similarities in physical and mechanical properties, with a clear advantage for "L" grades in terms of resistance to corrosion problems induced by welding or other thermal cycles, the use of type-standard carbon content grades is discouraged in favor of "L" grades for most critical containment materials. Furthermore, because of increased cost and the likelihood for embrittlement under some conditions for Types 316/316L compared with Type 304L, selection of materials other than Type 304L is further discouraged.

Extensive description of fabrication and design practices, and data tables for the physical and mechanical properties of stainless steels, including Type 304L, can be found in the open literature.^{[1], [2], [3]}

9.2.2 Carbon Steel

The primary strength of plain carbon steel as a material of construction is that it is inexpensive and can be processed in a wide variety of forms to develop a broad range of physical and mechanical properties. Its primary weakness is that it has very limited corrosion and oxidation resistance and can be prone to brittle behavior under some service or processing conditions. Plain carbon steels are iron-based alloys with specific carbon contents and only small amounts of other elements that are necessary in the steel-making process; no intentional alloying elements are introduced. Typically, the

designation of plain carbon steel is a four-digit number of the form 10XX, where XX represents the nominal carbon content in hundredths of a weight percent (0.00XX).

Many attempts have been made to generate a standard way of classifying and designating steels. Basically, these classification schemes group the steels by chemical analysis or composition, mechanical properties, or use. Typically, the methods based on mechanical properties and use are related to specific industries. A large number of methods are based on chemical analysis. Probably the most commonly used designations in the United States are those developed by either the American Iron and Steel Institute (AISI) or the Society of Automotive Engineers (SAE). These designations are essentially the same; each uses a four-digit code for both plain carbon and low-alloy steels. Sometimes, the AISI code is preceded by a letter indicating a particular method of manufacture.

Another set of designations frequently used are those developed by the American Society for Testing Materials (ASTM). ASTM issues individual specifications, each of which covers a specific steel form (i.e., bar or plate) or use. In the case of steels, these specifications are all preceded by "ASTM A" and include a number indicating the specification, which may also include subsequent letters or numbers that further subdivide the materials by analysis. For this purpose, the ASTM code frequently includes the AISI designation. The complete ASTM code also includes the year of origin and may contain a "T," indicating that the specification is tentative.

Plain carbon steels with nominal carbon contents ranging from 0.05 to 0.2 wt % (such as AISI 1015) could be termed "low-cost, low-strength, low-carbon steels." If the impurity levels (especially phosphorus, sulfur, and oxygen) are kept low, these steels can exhibit good weldability because of their corresponding low hardenability and can also have good ductility. Typical uses include ship and boiler plate; pipe; reinforcing bars (re-bar); and corrugated or deep-drawn sheet.

Plain carbon steels with nominal carbon contents ranging from 0.25 to 0.45 wt % (such as AISI 1030) are considered medium-strength, low-cost steels. They are hardenable by thermal treatment and cold working to a degree proportional to their carbon content. Properties are also controlled by the amount of impurities that tend to assist in hardenability while decreasing ductility. Silicon and manganese, which have little, if any, effect on properties, are added to some extent in all of these steels to help control oxygen and sulfur content during manufacture.

Plain carbon steels with medium high carbon-content ranging from of 0.5 to 0.8 wt % (such as AISI 1060) are typically used where high hardness is required but good ductility and toughness are not. These materials are likely to be suitable for container components. These materials are readily available in the form of sheet, bar, tube, castings, and forgings, but they are not usually found in thin sheet or tubing because the forms require frequent annealing to avoid embrittlement during manufacture, which increases the cost.

For a given plain carbon steel, its properties and suitability for certain uses are controlled by thermal treatment, working condition, and foundry practice. Typical heat treatments for plain carbon steels involve heating the material above the transformation temperature (the temperature at which all constituents are in a single-phase, solid solution called austenite) and cooling rapidly (such as quenching in oil or water to form a supersaturated solution that is typically strong, hard, and brittle) or cooling slowly in a closed furnace or air (normalizing) to produce a softer, weaker, more ductile material. Stress relief heat treatments and tempering heat treatments are performed after quenching to restore some ductility and toughness to a hardened steel at the expense of some strength loss. Scale removal by grit blasting or pickling may be required after thermal treatments.

The choice of fabrication temperatures or practices influences mechanical properties, machinability, and dimensional stability. In addition to hardening by heat treatment, steels can also be work hardened through plastic deformation at or near ambient temperatures. This procedure, called cold working or cold finishing, increases strength and hardness but decreases ductility and toughness. Cold working requires more power because the material becomes less ductile (work hardens) as it is formed. Intermediate annealing to recrystallize and soften the material may be required with cold working. However, cold working is a dimensionally precise fabrication method that can produce a readily machined part without the problems associated with oxidation. Hot working is performed above the transformation temperature of the steel so that recrystallization occurs simultaneously with plastic deformation, preventing work hardening. Hot working requires less power but makes final dimensions less precise and can cause surface problems because of the formation of oxidation/corrosion products.

Foundry practice, particularly the extent of deoxidation, can also influence mechanical properties of steel. Rimmed steels are only slightly deoxidized, allowing some evolution of gas (produced by available oxygen reacting with carbon) to occur during solidification. As a result, the outer skin of the ingot is depleted in carbon. If the rimming action is

controlled and if the carbon and manganese contents are not too high, the surface that is produced can be ductile. Thus, plain carbon steels are specified as rimmed steels that are suitable for processes such as cold rolling. Killed steels are fully deoxidized (usually by additions of aluminum or silicon), and they are typically chemically homogeneous with uniform mechanical properties and improved low-temperature toughness. The uniformity of killed steels makes them most suitable for applications involving hot-forging, cold extrusion, carburizing, and thermal treatment. However, killed steels are not particularly suitable for applications where especially fine surface finish is important. Semi-killed steels are not fully deoxidized, but they offer slightly better surface properties. They are suitable when neither the surface quality and cold working attributes of rimmed steels nor the uniformity of killed steels is required. Capped steel cools with some concurrent oxygen evolution (not as much as with rimmed steel) and has poor homogeneity, but it has good surface properties. Capped steels are used primarily for cold working.

Plain carbon steels, almost independent of heat treatment condition, experience a ductile-brittle transition as the temperature is lowered. Often, the transition is marked by a very significant decrease in notch toughness as the temperature decreases. Many factors influence the ductile-to-brittle transition temperature (DBT), but it is typically in the range of -20 to +20 °C for a typical 1040 steel. Notch toughness may decrease from the material's maximum to near zero over a 40 to 50 °C decrease in temperature.

A thorough summary of applicable steel specifications is given in *Metallic Materials Specification Handbook*.^[4] This reference categorizes the plain carbon steels by carbon content and provides a good summary of some representative properties for each group, including specific gravity, coefficient of thermal expansion, density, specific resistance, solidus/liquidus temperature range, Young's modulus of elasticity, thermal conductivity, impact strength, and tensile strength and elongation at various temperatures. The handbook contains comprehensive narrative summaries of each group of steels and a detailed listing of applicable foreign and domestic specifications. Specification listings for each group of plain carbon steels contain a nominal analysis, the supplier, the condition, and remarks indicating the use and/or hardness, tensile strength, elongation, and proof strength of the group. Other references contain general and specific information on classification and specification of plain carbon steels.^{[2], [3]}

9.2.3 High-Strength Steel

High-strength, medium-carbon steels with two or more alloying elements (such as chromium, nickel, molybdenum, tungsten, and vanadium) are a wear-resistant,

high-strength choice for springs, studs, bolts, nuts, and all forms of stressed engineering applications. These "high-strength low-alloy" (HSLA) steels, such as AISI 4340 (0.4 C, 0.8 Cr, 1.8 Ni, 0.25 Mo), have a carbon content high enough to ensure a minimum strength of about 900 MPa (>130 ksi) when fully tempered. The upper limit of the carbon content for this group of steels is near the eutectic point; therefore, even in the fully hardened condition they will retain some ductility. High-strength steels are fairly expensive materials; since their corrosion resistance in the hardened state is only marginally better than that of plain carbon steel, they must be protected. These steels should be kept dry, oiled, or greased if not permanently protected through carefully controlled plating or other treatment. Hydrogen embrittlement can be a problem for these steels if they are not stress relieved during or after processing.

Most high-strength steels have chromium as an alloying element because it increases hardenability of components with thick sections and slightly increases corrosion resistance. Nickel is frequently added to strengthen the iron matrix while providing increased toughness, low-temperature ductility, and fatigue strength. Molybdenum, another carbide former, acts as a grain refiner that also increases fatigue strength and facilitates hardening without temper brittleness by preventing carbide precipitation. Vanadium and tungsten alloying additions have a similar grain-refining effect on high-strength steels attributed to the formation and distribution of carbides. The choice of alloying elements actually used will depend on whether maximum hardness or ductility is required and may be influenced by cost.

9.2.4 Aluminum Alloy 6061

Aluminum-magnesium-silicon wrought alloys are a range of heat-treatable aluminum alloys characterized by excellent cold working properties. They are suitable for extrusions and have good corrosion resistance characteristics while possessing good mechanical strength. These alloys show less loss in corrosion resistance per proportional increase in mechanical properties than other heat-treatable aluminum alloys. The alloys should be anodized for structural applications. Aluminum 6061 is a medium-strength, structural Al-Mg-Si alloy. It is a heat-treatable, wrought alloy used for a majority of extrusions. Small quantities are used for sheet and plate. Common forms of the alloy are available in natural aged (T4 and T451) or artificially aged (T6 and T651) forms. An as-fabricated form, O, is available but has inferior properties when compared with others. AL 6061 has good weldability, corrosion resistance, and immunity to stress-corrosion cracking. Balanced amounts of magnesium and silicon (1.0 wt % magnesium and 0.6 wt % silicon) are added to form a quasi-binary Al-Mg₂-Si alloy. Copper (0.25%) is added to improve mechanical properties, and chromium (0.2%) is

added to offset the adverse effect of the copper on corrosion resistance. Iron, titanium, zinc, and manganese are also present in the alloy.

An oxide layer quickly forms on the surface of the metal. Such layers are generally 3 to 5 mm thick, although no equilibrium is reached. Oxide will continue to form, although at a greatly reduced rate. This oxide forms more rapidly in higher temperatures or with increasing humidity. However, the oxide film is generally stable and protects the metal. Thick oxides with improved surface adhesion are sometimes generated to increase corrosion resistance with a hot acid or alkali bath that may contain chemicals, such as chromates, to yield an even higher corrosion resistance. Even thicker coatings are made with anodic processes. The aluminum is made from the anode in an electrolytic solution, such as a 15% sulfuric acid aqueous solution, and then it is sealed by dipping it in boiling water or chromate solution.

Both the naturally and the artificially aged forms of the alloy are solution treated at 530 °C then quenched at room temperature. Mechanical properties of the artificially aged alloy are considerably different from the naturally aged alloys. Tensile strength of the alloy improves by approximately 20% with artificial aging. T6 and T651 alloy are nearly 50% harder, with elongation decreasing by a like amount.

Generally, strain hardening has little effect on heat-treated alloys, although high rates of strain may be used in wire, rod, and tube stock of T6 and T651 alloys to improve strength and surface finish.

Information on aluminum alloys is readily available from the Aluminum Company of America (ALCOA). Specific information on alloy properties and specifications can be found in various volumes of the *Metals Handbook*.^{[2], [3]} *Metallurgy of Light Metals* contains information on the fabrication and properties of aluminum.^[5]

9.2.5 Cellulosic Insulating Board (Celotex™)

Cellulosic insulating board (or Celotex™) is a fibrous-felted panel board made from ligno-cellulosic fibers (usually cane) characterized by an integral bond of interweaving fibers. Other ingredients may be added to provide or improve certain properties such as strength and water resistance, and special coatings may be used to impart resistance to flame spreading. The homogeneous boards have density ranges of 10 to 31 lb/ft³, and a maximum moisture content of 10 wt % as shipped from the manufacturer.

In packaging applications, insulating board serves a multifunctional role as a positioning, thermal insulating, and energy-absorbing (cushioning) material. Generally, it would be

used between a drum and containment vessel to protect the CV from thermal and mechanical damage during NCT and HAC. The lightweight board is a readily available commercial product that can be easily cut or drilled to the desired design configuration.

As the cellulosic insulating board is essentially of organic composition, it will undergo combustion in air with an ignition point of about 450 °F. The combustibility may affect design decisions for packaging applications involving hypothetical accident scenarios with specific thermal protection and testing criteria. Design modification or compensation, to protect the CV thermally from short-term combustion effects, might include increasing the wall thickness of the insulating board, using of fire-retardant coatings on the board surfaces, or both.

9.2.6 Inorganic Refractory

An inorganic refractory material has been developed for use as an impact absorbing and thermal insulating material in drum-type radioactive material shipping packages.^[6] The material that has been used is Kaolite 1600™ made by Thermal Ceramics, but many other similar materials are available. This inorganic refractory is composed of Portland cement and expanded vermiculite. It possesses excellent energy absorption characteristics during impact loading making it an excellent choice as an impact absorber. Since the material's original intended use is as a refractory material within high-temperature furnaces (Kaolite 1600™ has a maximum recommended continuous use temperature of 1600 °F; thus the name) it withstands the rigorous environment of the HAC thermal test without any discernable degradation. Its inorganic nature means that the only volatile gas formed during heating is steam which typically condenses at about 212 °F. No hydrocarbon volatiles, which may have considerably higher condensation temperatures, are formed.

Material densities of 20-26 lb/ft³ are typical. Recent study suggests the density can be closely controlled by varying the mixing time prior to pouring. Structural and thermal characteristics vary only slightly from the most dense to the least dense specimens, and there is little variation in these properties with temperature. Kaolite 1600 is fireproof at HAC temperatures, and maintains its impact-absorbing attributes after exposure to high temperatures.

9.2.7 Ceramic Fiber Materials

Insulations based on ceramic fibers have been used in many applications, particularly following the energy crisis in the early 1970s. Strictly speaking, Fiberglas™ is a ceramic

fiber but is usually considered to be a separate generic-type product. Base fiber compositions vary widely, depending on application, from common silicates to pure materials such as alumina and zirconia.

Ceramic fiber insulation is commercially available in a wide variety of forms such as paper, woven cloth, tape, felt, flock, sheet, batt, and boards in both semirigid and rigid form. *Thermal Insulation* gives a detailed discussion of general characteristics and applications of the various forms.^[7]

The ASTM C-16 committee activities have been invaluable and vital to insulation technology and have resulted in a degree of uniformity in prescriptions for testing insulations, 12 symposia on insulations since 1952, and commonly accepted specifications and standards. Manufacturers often claim to meet or exceed ASTM specifications; however, these specifications generally represent the "lowest common denominator". Reference 7 contains extensive tables of data on chemical, physical, and thermal properties of all generic insulations, including ceramic fiber, that are in general use in industry.

Because of cost, ceramic fiber insulations are generally used only in high temperature applications. However, moisture absorption must be considered for applications that involve lower temperatures because of property changes due to low density and very high surface area. In addition, the insulation may release significant volatiles upon first heating, or when exposed to ambient conditions following the first heating.

9.2.8 Fir Plywood

Plywood is composed of thin sheets of wood (called veneer or plies) bonded with an adhesive. The grain of each ply is set at a 90° angle to the adjacent ply. This distinguishes plywood from glued laminated timber (glulam), the grains of which run parallel to each other. The plies range from 1/12 to 7/32 in. thick. On an equal weight basis, plywood is about 1.5 times stronger than steel and is therefore a light-weight, high-strength material.

The cross-grain construction of plywood gives it certain advantages over ordinary lumber. Wood is very anisotropic, having considerably lower tensile strength perpendicular to its grain than parallel to its grain. The strength of plywood is nearly the same in either direction. Plywood normally is composed of an odd number of plies to keep it balanced around the center ply. The balanced construction allows plywood to be used in sheets that are narrower than ordinary lumber and allows fastening with nails or

staples much nearer to the edge. Depending on humidity levels, ordinary lumber will shrink or expand from 3 to 6% across its grain while experiencing very little longitudinal change because the modulus of elasticity parallel to the grain is about 20 times greater than it is across the grain. Also tangential shrinkage is about twice radial shrinkage, which leads to twisting or warping of the wood and an uneven distribution of moisture, which can lead to cracking or splitting at the ends. Because of the strength of the adhesive bond, plywood resists the tendency to expand or contract; the shrinkage of plywood is about 1/10 that of lumber. The balanced cross-ply construction reduces warpage, and the cross-grain construction reduces splitting at the edges. Any deviation from the 90° angle of the adjacent plies diminishes the ability of plywood to restrain dimensional change. Another advantage is that plywood can be made in sheets much larger than boards sawed from logs.

Plywood comes in a number of grades. The Department of Commerce, National Bureau of Standards, issued U.S. Product Standard PS 1-83, which has been adopted by the American Plywood Association (APA), formerly the Douglas Fir Plywood Association.^[8] The standard defines five groups of trees, classified according to the stiffness of the lumber, used in the production of plywood. Before the PS 1 standard was issued, specifications were contained in the Commercial Standards (CSs) of the Department of Commerce. The CSs were written in parts specific to four trees, one of which was the Douglas fir, the softwood most commonly used in plywood production. Under the PS 1-83 standard, Group 1, the highest stiffness grade, includes Douglas fir grown in northwestern regions, Southern pine, and many others. Douglas fir grown in southwestern regions are in Group 2. The standard covers appearance grades as well as engineering grades. The appearance of the plywood is ranked N if the face veneer is cut only from heart-wood or sapwood that is free of open defects. N-graded plywood can receive a natural finish. Other veneer grades range from A through D, wherein the number of allowable defects such as knot holes, patches, or cracks is defined. Only the outside plies (the face veneer) are graded by the standard, and sometimes the two face plies can be of a different grade. Engineering grades are usually C-C or C-D appearance grades and are available as Structural 1, Structural 2, Underlayment, and Plyform grades. For demanding applications requiring the strongest material, Structural 1 material, which can be made from only Group 1 trees, is recommended.

The standard also defines exposure durability grades, depending on whether the adhesive used between the plies can withstand continuous exposure to moisture without delamination. The adhesive used in exterior grades is usually phenol formaldehyde, which leaves a reddish-brown stain along the bondline but can produce

bonds that are more durable than the untreated wood itself. Melamine formaldehyde is more expensive but can be used if staining is undesirable. Because wood is susceptible to environmental decay, the faces of exterior plywood should be stained, coated, or painted to prevent ultraviolet deterioration if used in an exposed position. For long-term exterior exposure, pressure-treated plywood works even better. Exposure 1 plywood (CDX) is made using exterior adhesives, but the faces are less rugged than in exterior grades unless they have been pressure treated. Exposure 2 plywood is bonded with phenol formaldehyde, but the faces are so delicate that it should be used only for interior applications. Exterior and Exposure 1 and 2 plywood can be used in place of vapor barriers if joints are sealed with glue or a vapor barrier tape. Interior grades are bonded with urea formaldehyde, which is inexpensive but strong and tough. Bond strength will be maintained under occasional exposure to moisture, but prolonged exposure will deteriorate the bond.

Plywood carries an APA stamp that shows its exposure durability, appearance grade, engineering grade, and other information. The thickness of the panel may also be listed. Plywood is usually available in thicknesses ranging from 1/4 to 3/4 in., and the boards are usually 4 by 8 ft.

For design purposes, plywood is considered to be homogeneous, orthotropic plates. Mathematical formulas have been developed to compute stiffness and strength, stress at proportional or ultimate limits, or estimates of working stresses. The formulas use section properties, which depend mainly on the characteristics of the face plies and the direction of the grain relative to the direction of the stress. The section properties are independent of the number of plies in the panel. The section properties have been determined by the U.S. Forest Products Service and are called out in the PS 1-83 standard. The APAs "Plywood Design Specification" tabulates section properties and recommended design stresses and methods for the large number of possible combinations of grades and panel thickness (American Plywood Association, P.O. Box 11700, Tacoma, WA 98411-0700, (206)-565-6600). There are a large number of publications about plywood, in particular, the *Wood Handbook* contains useful information.^[9]

9.2.9 Redwood

Redwood is an American softwood tree that typically is moderately light, strong, stiff, and hard. It is easy to work, generally straight grained, and shrinks or swells comparatively little. The heartwood resists decay, making it useful for a number of

outdoor applications, such as fence material, outdoor furniture, or long-term storage applications.

In general, redwood properties can vary from tree to tree within a species and even from piece to piece by as much as 25%. Also, properties are dependent on the direction of the grain. Other considerations that may cause redwood properties to vary include age of the tree, water content, and type of wood (heartwood or sapwood).

The specific gravity of dry, young-growth redwood is approximately 0.35 (35% that of water). Water content of the wood can range up to 100% of its dry weight, although commercially available wood is usually 12% or less. It is the most dimensionally stable of any common American wood with volumetric changes limited to about 7%. Typical values for mechanical and other properties of wood may be found in the *Wood Handbook*.^[9]

9.2.10 Urethane Foams

A broad range of urethane foams are readily available to the package designer and are often a material of choice. Polyurethanes are derived from the additional polymerization of polyols and polyisocyanates. Flexible foams depend on polyester polyols for good elongation and tensile strength properties and polyether polyols for better hydrolysis resistance and resiliency. Further improvement in resiliency can be obtained from polymer polyols of more complex structure. Rigid urethane foams are the general material of choice for thermal insulation and impact energy absorption. The rigid foams are cross-linked, closed-cell polymers with a low density. They have good resistance to chemicals and solvents and can be used over a temperature range of -55 to 135 °C. Their superior insulation properties are derived from the fact that the closed cells entrap the blowing agent, yielding foams with an extremely low coefficient of thermal conductivity. Other important characteristics include good low- and high-temperature dimensional stability; low permeability to water vapor and moisture; and good compressive, tensile, bending, and shear strengths.

The development of polyisocyanurate foams provides rigid foams with improved flame retardance.

Some properties to consider in the selection of a flexible foam are density, tensile strength, tear strength, elongation, flexural fatigue, flammability, solvent resistance, load deflection and indentation, rebound, and humidity aging. It is difficult to formulate as many as seven requirements into a given foam and still hold it within the desired

tolerances; especially if cost is a major factor. Most often, the formulator can give the end user very close tolerances on the four or five most important properties and reasonably close proximities on the next two to three properties. Therefore, it is important that the end user consider carefully the most stringent requirements and present required properties of major importance in the first four to six listings.

Several testing methods exist for flexible urethane foams. Some of these testing methods give fairly accurate data on how the foam will perform in its intended environment while other tests provide data that are much less accurate. Among the helpful tests that give reasonably accurate data are the ASTM D 2406 series, which includes the following tests: steam autoclave, compression-set, load-deflection (indentation), compression load-deflection, dry-heat, fatigue, density, tear resistance, and tensile strength. ASTM 1564 is also useful in tear resistance tests.

Rigid urethane foams are far superior to any other polymeric foam in thermal insulation properties. Values are sometimes misleading, but the K-factor of these foams surpasses that of any known insulating material by at least 20% and more. This fact allows lesser quantities to be used or better insulation properties for the same thicknesses of material.

A number of clear-cut methods are available for testing the properties of rigid urethane foams, including ASTM, SPI, and various governmental agencies that have testing methods and specifications. Table 9-3 gives ASTM specifications for testing these foams.

There are many variations of such tests by ASTM and others involved in the industry. SPI has many excellent test methods. Various governmental agencies have tests that more closely meet their specific property requirements. All such tests are good, and the testing methods used will depend to some extent on the end use of the foam, the density, and various other factors. For instance, one test method may be better for a 2-lb density foam whereas another method may do a better job on a 12-lb density foam.

Testing for K-factor (thermal conductivity) is the most controversial of all the testing methods. Manufacturers of foam systems sometimes make claims of K-factors by their private testing methods. These will seldom coincide with the K-factor if done by strict ASTM specifications. The manufacturer usually gives the original K-factor reading on the foam immediately after curing. This figure begins to rise immediately, as some of the gas in the cells begins to permeate out, and is replaced by air. A foam with a K-factor

Table 9-3. ASTM Specifications for Testing Rigid Urethane Foams

Property	Specification
Density	ASTM 1564-58T
K-factor (Btu/h-sq ft ² /°F/in.)	ASTM C 177
Water Absorption	ASTM C 272-51T
Coefficient of thermal expansion	ASTM D 696
Compression load	ASTM D 1621-59T
Flexural strength	ASTM D 790-59T
Flammability	ASTM D 635
Deflection temperature	ASTM D 648
Dielectric strength	ASTM D 149
Dielectric constant	ASTM D 150
Dissipation factor	ASTM D 150
Volume resistivity (ohm/cm)	ASTM D 257
Arc resistance	ASTM D 495
Tensile strength (parallel and perpendicular)	ASTM C 297-55
Tensile strain (parallel and perpendicular)	ASTM 297-55
Tensile elastic modulus (parallel and perpendicular)	ASTM C 297-55
Adhesive strength	ASTM C 297-55

reading of 0.13 immediately after curing may well have a factor of 0.19 at the end of 6 months. After 6 months, the K-factor changes little at normal temperatures and normal conditions.

A good 2-lb density foam blown with water will have an initial K-factor of about 0.16, which will increase to about 0.21 after 6 months. The same foam, blown with a fluorocarbon, will have an initial K-factor of about 0.14 and will increase to about 0.18 after 6 months. These are good representative foams for thermal insulation.

Water absorption is another test that causes some controversy in the industry. Many systems manufacturers have testing methods of their own that show more favorable results than would result using standardized methods. A 2-lb density foam that will pick up under 3% water by volume in a 7-d test and less than 7% in a 180-d test is considered to be an excellent foam.

Tests must be run on foams in accordance with the requirements of the end product. All the tests listed will be required on very few foam applications. If a foam were to be used as a structural material, tests would have to be run on compressive, tensile, and shear strengths.

Tests should never be run on a single sample batch. A minimum of three batches of a given formulation should be poured. Samples from these three batches should be tested for the required properties and averages taken. In this manner, statistically accurate values may be obtained. There will always be variations from mix to mix, particularly if the sample batches are hand mixed. Whenever possible, sample batches should be run with the same proportioning and mixing equipment that will be used in the final process, thus giving much closer values for the manufactured foam.

9.2.11 Silicone foam

Silicone foams are generally composed of silicon-oxygen compounds that are considered similar in nature to an organic polymer, except that silicon atoms are substituted for the carbon atoms. Silicone foams have several advantageous properties such as their nonburning quality, good electrical insulation, low water absorption, and excellent thermal stability.

Three types of silicone foams exist; premixed powders, room-temperature curing resins, and elastomeric foams. The oldest type is the premixed powders, which consist of a polysiloxane resin blowing agent and fillers. This mixture is heated above 160 °C, causing the resin to liquefy and the blowing agent to decompose. Nitrogen gas expands the resin, and amines that are released act as catalysts for condensation of the resin. Thus, the expansion and gelation are synchronized so that the resin gels at maximum expansion.

There are three types of powders: Type A, which can be foamed to densities ranging from 0.16 to 0.22 g/cc; Type B from 0.19 to 0.26 g/cc; and Type C from 0.22 to 0.29 g/cc. Types A and B can be foamed in place and are more resistant to thermal shock than is Type C. Type C can be foamed only as a block or sheet and is stronger than Type A or B. Type C also retains more compressive strength than Type A or B at high temperature.

The room-temperature cure foams are generally a two-liquid silicone component system in the presence of a catalyst producing either flexible or rigid foams. The reaction is slightly exothermic, but temperatures seldom exceed 62 °C. Hydrogen gas is liberated

as the expanding agent in these foams. Generally, these foams are blended in a high-speed mixer for 30 s and poured. They expand to 7 to 10 times their initial volume. The reaction is complete in 15 min, but the foam remains soft for about 2 h. The foam is hard enough to cut and handle after approximately 10 h with maximum strength obtained in 24 h. Continuous service temperatures of these foams range as high as 350 °C.

Elastomeric silicone foams are lightweight, rubbery foams that are also made by mixing two components. The mixing requires about 30 sec and the materials must be poured immediately because expansion occurs immediately upon blending. After approximately 5 min, the foam will have developed 80% of its ultimate strength. Maximum strength is generally obtained after 24 h.

Properties of silicone foams depend on both the density of the foam and whether the cell structure is open or closed. Densities of flexible silicone foams can range from 0.11 to 0.54 g/cc. Tensile strengths of these foams are generally low, in the range of 0.1 to 1.0 MPa; however, compression sets of less than 1%, chemical inertness, high electrical resistivity, good insulation value, and self-extinguishing characteristics make them an excellent cushioning material. Continuous service temperatures are typically 250 to 350 °C for the commercially available materials. Physical property data for some of these foams can be found in the literature.^{[10], [11]} Vendor literature provides the best source of property data because commercial offerings vary significantly.

9.2.12 Ethylene Propylene Elastomer

Ethylene propylene monomer (EPM) rubbers are copolymers of ethylene and propylene that are incapable of forming substantial rigid, crystalline phases and are therefore amorphous and rubbery. Vulcanizates or crosslinked rubbers are produced by incorporating unsaturated comonomers into the EPM, which yields sulfur and peroxide crosslinkable materials called ethylene propylene di-monomer (EPDM). The EPM and EPDM rubbers are almost always used in a compounded and crosslinked EPDM form that has many of the attributes associated with other polyolefins, such as excellent resistance to acids and alkalies, poor resistance to hydrocarbons, good low-temperature mechanical properties, and good electrical properties. As a class, the ethylene-propylene rubbers have good compression set characteristics and the best elevated temperature performance of the commodity rubbers.

Ethylene-propylene rubbers, particularly EPDM, are commonly used as O-ring seals in Type B packages. The usual fabrication method for EPM and EPDM is extrusion, such

as for hose and strip, while single shapes can be made by compression or transfer molding. Sponge gasket material is also available. The densities of commercially available polyethylene-type polyolefins range from approximately 0.88 to greater than 0.96 g/cc. Polypropylene usually has a density ranging from 0.90 to 0.91 g/cc. The densities of ethylenepropylene copolymers depend on the ratio of the comonomers and the type and proportion of fillers.

9.3 FABRICATION

The following fabrication methods have been successfully used in packaging design: Machining, Forming, Forging, Heat treating, Welding, Bolting, Bonding (glue), Plating, and Painting. Other methods may be used, but justification must be documented.

The following sections address the use of these fabrication methods for each of the applicable materials used in special nuclear material packagings. If a particular material is not discussed under a specific fabrication method, then that fabrication method is not typically applicable to the material.

9.3.1 Machining

9.3.1.1 Austenitic stainless steel

Austenitic stainless steels are readily machinable by a variety of conventional methods such as drilling, turning, and sawing, but they also have problems. Each has a high work-hardening rate and, because of high ductility, may become gummy (stringing, tangled chips) during machining. Work-hardening effects can be minimized by maintaining feed rate above minimum for the material and performing the operation continuously. Sufficient working during machining may introduce slight magnetic character (as a result of a strain-induced phase transformation) into the otherwise nonmagnetic material. A common example is that the threads on some Type 304L bolts are slightly magnetic.

9.3.1.2 Carbon steel

Machinability of carbon steel is controlled mainly by carbon content, impurities, and hardness. The lower carbon steels are difficult to machine with a good surface finish without the addition of additives such as sulfur, phosphorus, lead, or tellurium. The poor surface finish can be minimized by hardening the material before machining; however, this process is not economical for the lower carbon steels. With the exception of the specially developed "free machining" steels, the medium carbon steels are probably the

most readily machined of the plain carbon group due largely to their hardenability. Typically, these materials are machined by a variety of conventional methods such as turning, milling, drilling, and sawing in the hardened or tempered condition to achieve the best surface finish. High hardness and uniform distribution of oxide inclusions facilitate machining to a good surface finish. The higher carbon steels are more difficult and more expensive to machine. In general, if machining is required, semifinish machining is performed on material in the normalized condition followed by hardening or tempering of the material before machining to final dimensions by grinding. Processing required to achieve hardness can cause distortions that may have to be compensated for in machining.

9.3.1.3 High-strength steel

Many high-strength steels will be too hard to machine after hardening and tempering because they will be above 1170 MPa (>170 ksi) tensile strength. The best condition for machinability is hardened and tempered at 1000 MPa tensile strength, and for some purposes it may be necessary to obtain this condition through re-hardening and tempering before final grinding. Annealing at a temperature of 650 to 670 °C for 2 h removes most cold work stress before machining. For normal purposes, the steels should be rough machined in the normalized and annealed or spheroidized condition (depending on composition), which generally results in some tearing, then finally ground after hardening and tempering. Where parts are machined from rough materials in the finally hardened and tempered condition, it may be advisable to stress relieve at the tempering temperature before final machining. High-speed or tipped tools are essential for cutting these steels. Spark erosion and electrochemical machining techniques can be used to shape fully hardened parts, but they will seldom be economical.

9.3.1.4 Aluminum alloy 6061

Aluminum 6061 is easily machineable by common methods in the heat-treated condition. Because of the presence of hard intermetallics, high-speed or tipped tools should be considered. Some minor problem may occur in chip formation, particularly in T4 and T451, because of their relatively higher ductility. T6 and T651 alloys are generally resistant to strain hardening, which makes them somewhat more easy to machine.

9.3.1.5 Insulating board (cellulosic fiber)

The insulating boards are readily cut to the desired shape using conventional woodworking tools. Standard wood drill bits, hole saws, and cutting saws (band, radial arm, table, and saber), can be used. Carbide-tipped bits or blades can be used but are not necessary. Fine-tooth saw blades are recommended to minimize tearing of the lightweight, fibrous material.

9.3.1.6 Ceramic fiber materials

Ceramic fiber materials present no major problems in machining using ordinary carpentry tools (e.g., saws, drills, files, and shears). Care should be taken to minimize dusting because some products might contain respirable fibers.

9.3.1.7 Fir plywood

Sharp knife techniques will produce less damage to the fir plywood structure than sawing. Knives must be kept sharp and properly aligned. Saws tend to tear the fibers more severely than knives; however, properly maintained saws can cut the wood fibers quite adequately. When cutting with a table saw, the good side of the wood should face up; with a portable electric saw, the good side should face down. End user sanding of the face veneers should be avoided. Panels with B-grade or better faces are sanded smooth in manufacture to fulfill the requirements of their intended end use. Some grades are only touch sanded for sizing to make the panels more uniform while some grades are left unsanded. End user sanding could lead to damage of the face veneer or to a lack of balance in the panel.

9.3.1.8 Redwood

The ease of working wood generally varies with the specific gravity of the wood, with the lower specific gravity woods being easier to work. Also, smooth-grain woods are generally easier to work; therefore, redwood is relatively easy to work with common woodworking techniques. However, redwood is also fairly easily to split, so care must be taken, depending on the grain direction and the operation being performed.

9.3.1.9 Urethane foam

Urethane foams, regardless of density and open or closed pore status, are best machined by dry grinding methods. The dust produced may be treated as a nuisance dust. Hot wire cutting and shaping may be undertaken for simple shapes. Best thermal

protection performance can be achieved by a "foamed in place" approach when the application and the exothermic reaction will allow.

9.3.1.10 Silicone foam

Silicone foams are best machined by dry grinding; however, the very high elongation to failure of the base polymer makes exact dimensions difficult. The softer materials are better foamed to shape. Thermal protection performance is enhanced by "foamed in place" applications.

9.3.1.11 Ethylene propylene elastomer

The ethylene propylene elastomer is generally molded to shape, because its low modulus and high tear strength do not allow conventional machining operations. The material may be die cut but with some difficulty.

9.3.2 Forming

9.3.2.1 Austenitic stainless steel

Cold working (plastic deformation below recrystallization temperature) is a common forming method for stainless steel. In the initial stages of cold work, austenitic stainless steels are readily formable, but as the degree of work increases, work hardening (and therefore the power requirement) increases. Depending upon the degree of work required, stress relief or solution treatment may be required following cold working. Hot working involves plastic deformation at temperatures above recrystallization temperature. Hot working requires less power and typically presents few cracking problems as a result of work hardening, but it is more difficult to control in terms of potential oxide contamination of surfaces and precise dimensions of finished components. These materials are readily suited to bending, rolling, drawing, extruding, punching, and other forming operations with appropriate attention given to temperature, extent of work, and other control variables.

9.3.2.2 Carbon steel

Forging, drawing, extruding, rolling, and other forming processes are standard operations in the fabrication of plain carbon steel.

The deoxidation practice used to make a steel will affect its suitability for forming. One of the cheapest steels suitable for many forming applications is hot-rolled, commercial quality, rimmed steel. For an increase in cost, better surface finish and superior

formability are available with cold-rolled drawing quality, special killed, and temper-passed steel. Killed steels are preferred where uniform mechanical properties and severe forming applications are required, although they may be less tolerant to handling damage and may have inferior surfaces. A consideration when using rimmed steels is that they can strain age, especially after working, which can change their subsequent formability characteristics. Artificial aging can be used to prevent this effect without appreciably altering tensile strength; however, yield strength and hardness will increase and elongation will decrease.

9.3.2.3 High-strength steel

These steels cannot be cold worked to any great extent without becoming too brittle for practical use. Some wire specifications are cold drawn and tempered, and some bar alloys have final cold-sizing passes, but in general, full annealing between cold-working operations will rarely be required because these materials are almost always hot worked and then heat treated to establish mechanical properties.

Warm forming may be used to process these steels to protect against loss of mechanical properties already established. Typically, this is accomplished by heating the material close to the temperature at which it was previously tempered and forming immediately.

9.3.2.4 Aluminum alloy 6061

Aluminum 6061 can be extruded, rolled, shaped, and formed into sheet or plate. Cold working has little effect on the artificially aged T6 and T651 alloy forms, although it can be useful in adding strength to the T4 and T451 alloys. The artificially aged forms may be annealed to improve ductility as desired.

9.3.2.5 Inorganic Refractory

In applications to date, Kaolite 1600™ is encapsulated between a drum and an inner liner. The material is initially mixed with water as specified by manufacturer. The material is poured into place, typically through a hole made in the bottom of the drum. The material is vibrated as it is poured to ensure that no sizable voids occur. After a drum has been filled, it is allowed to sit for a minimum of 24 hours at ambient conditions while the mixture sets up. After this period, the package is heated to 260 °C incrementally and held there for about 48 hours. After cooling, the hole through which the Kaolite was poured is covered.

9.3.2.6 Redwood

Redwood stock may be pressure treated or steamed to curved contours, but the practice is not recommended for long-term applications under normal storage conditions.

9.3.2.7 Urethane foam

Urethane foams may be blown into complex molds or formed in place if required by packaging design. Adhesion to the surrounding mold or container walls can be adjusted by surface preparation and mold release compounds.

9.3.2.8 Silicone foam

Silicone foams can be easily molded to desired shapes. Mold pressures are low, and the polymer flows well during the foaming step. The cure is rapid with very little shrinkage. Complete cure properties are obtained in less than 24 h. However, care must be taken during the foaming operation to follow the manufacturer's instructions exactly if the foam is to be molded and removed from the mold for further use.

9.3.2.9 Ethylene propylene elastomer

The usual fabrication method for ethylene propylene elastomer is extrusion for continuous product. Compression or transfer molding is appropriate for single shapes. Gaskets and O-ring seals may be either molded solid or as a self-skinning sponge.

9.3.3 Forging

9.3.3.1 Austenitic stainless steel

The typical working temperature for forging of Type 304L stainless steel is in the range of 900 to 1200 °C. At higher temperatures in this range, the possibility of the presence of ferrite (particularly during initial breakdown of a cast ingot) can invite cracking problems. This problem can be minimized by a solution treatment soak before forging and by lowering forging temperature. In addition, forgings finished below typical solution treatment temperature should be solution treated following forging.

9.3.3.2 Carbon steel

Carbon steels are readily forged into a variety of shapes using hot-, warm-, or cold-forging processes with standard equipment. Only the free-machining steels with

additives, such as sulfur, are difficult to forge. In general, forgeability increases with deformation rate and forging temperature decreases with increasing carbon content. Forging is typically performed at temperatures between 1200 and 1300 °C. The dimensions (thickness) and complexity of components that can be successfully forged from carbon steels are limited not by the material's forgeability but by the cooling of the hot workpiece when it contacts cold tooling. Forgings are usually purchased by specification in one of four conditions: heat treated for machinability, heat treated for final mechanical and physical properties, specially heat treated for dimensional stability, or heat treated as-forged.

9.3.3.3 High-strength steel

High-strength steels are readily forged into a wide variety of shapes using hot-forging methods. Warm and cold forging are used to a lesser extent because of the higher strength of these materials (and resistance to deformation) and the need to carefully control intermediate thermal treatment. Generally, hot forgeability improves with deformation rate and hot-forging temperature decreases with increasing carbon and alloying content. Forgings are usually specified in the as-forged or heat-treated condition. Various heat-treated conditions may be called out to indicate that the forging is to be machined after forging or that final properties are to be obtained. Other thermal treatments after forging may be specified to control dimensional distortion, residual stresses, surface hardness, etc.

9.3.3.4 Aluminum alloy 6061

Special care must be given to forging parts of Aluminum 6061. Generally, only T4 and T6 alloys are available for forging because the other forms use stretching to relieve built-in stresses caused by water quenching. Forgings are typically held at 175 °C for 8 h. Forgings may be more susceptible to cracking because of the chromium content of the alloy.

9.3.4 Heat treating

9.3.4.1 Austenitic stainless steel

Heat treatment of Type 304/304L and Type 316/316L grades of stainless steel is typically performed to homogenize the material composition (most commonly to return chromium carbides to solution) or to provide stress relief following welding or some forming operation. Solution treatment (sometimes called annealing) to return chromium carbides to solution is performed by soaking the steel at temperatures from 1050 to

1150 °C for 1 h followed by a rapid cool to room temperature (typically a water quench). Typically, temperatures at the low end of this range apply to Type 304/304L steels and temperatures at the high end apply to Type 316/316L steels. Stress-relief heat treatments are typically performed by soaking at temperatures from 500 to 900 °C (most common at the higher end of this range) followed by a slow cooling process. Potential problems include inadequate solution treatment or too much time stress relieving (both may generate carbides on grain boundaries), which compromise localized corrosion resistance in many environments. In addition, embrittlement of welds containing ferrite occurs during prolonged exposure in the temperature range from 400 to 800 °C with Type 316/316L alloys being somewhat more susceptible than Type 304/304L alloys.

9.3.4.2 Carbon steel

Low-carbon steels are commonly used for deep drawing sheet because of their low hardenability and good ductility. They require annealing only after considerable work. Annealing is typically performed in the 900 to 950 °C temperature range for about 20 min/in. of cross section followed by a slow cooldown. Scale will form at these temperatures unless the atmosphere is controlled (a reducing atmosphere is recommended over a neutral one). Normalizing, a similar process, is performed after forging and is recommended before any carburizing. The lower-carbon steels are typically not hardened and tempered because the practice does not warrant sufficient increase in strength or hardness to offset the expense.

Medium-carbon steels require intermediate annealing at temperatures near 900 °C (20 min/in.) after any significant amount of cold working. Normalizing (at temperatures around 900 °C for 10 min/in. of cross section followed by slowly cooling in still air) is usually performed after forging or other hot-working operation to reduce stresses, homogenize the structure, and increase ductility. Subsequent hardening is accomplished by heating to temperatures around 850 °C (for 10 min/in.) and water or oil quenching. Tempering is required shortly after quenching to avoid cracking or other stress-related problems. Specifics of tempering (time and temperature) will vary greatly, depending on the desired combinations of strength or hardness and ductility. Scale removal may be required by blasting or acid pickling after thermal treatment.

9.3.4.3 High-strength steel

It is important that high-strength steels are heated slowly to temperature for all thermal treatments to avoid distortion or cracking, especially where the workpiece has greatly varying section thicknesses. Sub-critical annealing for moderate times at temperatures

of 650 to 670 °C is used to remove cold work. Spheroidizing is performed on alloys containing appreciable quantities of chromium, vanadium, and tungsten to aid machinability. This cyclic heating process involves heating well into the austenitizing range (800 to 920 °C) for 30 min, transferring to a furnace at 670 to 700 °C for 2 h of soaking, and then repeating this two-step process one or more times. Spheroidizing creates a microstructure with finely dispersed, round carbides (hard particles) in a soft ferritic matrix. Normalizing (heating to 800 to 920 °C for 30 min and cooling in still air) is performed only when spheroidizing is not appropriate or required. The considerable air hardening that occurs during the normalizing treatment is tempered by a subcritical anneal performed at 650 to 670 °C.

Intentional, through-thickness hardening is accomplished by heating to 780 to 900 °C for 20 min/in. of cross section and quenching in oil or circulating air. Tempering is then performed without delay. A deep freeze treatment (-80 to -100 °C) is frequently used either following hardening or between multiple tempering treatments to stabilize the parts dimensionally and maximize hardenability.

Martempering is a special thermal treatment often used to reduce the residual stresses that develop while quenching from high temperature. This process involves heating to the austenitizing range, quenching into a hot medium such as hot oil or molten salt, stabilizing at the quench temperature, and then cooling at a moderate rate to room temperature in air. This process reduces the thermal gradients through the section, thereby reducing residual stresses and distortion. The effect of this benefit can be to simplify the fixturing normally required to prevent distortion during quenching, which can reduce processing costs.

Austempering is another thermal treatment used for these high-strength steels in place of conventional austenitizing, quenching, and tempering cycles. It is used to maximize ductility or notch toughness at a given hardness and to reduce distortion. If appropriate for use, it can result in considerable time savings over conventional thermal treatments for hardening or tempering. With austempering, the material is austenitized at 790 to 870 °C and then quenched to a molten salt bath that is held at a constant temperature slightly above the temperature at which the hard martensitic structure begins forming (typically the bath temperature is between 260 and 400 °C) until all the material has transformed isothermally to a structure called bainite. Then the material is cooled to room temperature in still air. No further tempering is necessary.

The specifics of any of these thermal treatments will be governed by the composition of the alloy properties or processing qualities desired. General information for many

classes of alloys and specific information on heat treating of selected alloys is available.^[3]

Unless the furnace atmosphere is carefully controlled during heat treatment, some scale will form. Scale can be removed by grit blasting.

9.3.4.4 Aluminum alloy 6061

Heat treating, generally called aging, is used in the T6 and T651 alloys to increase hardness and tensile properties. It can also be used to relieve residual stresses caused by quenching, although the T451 and T651 alloys use stretching to achieve some stress relief. Heat treating forms a finely dispersed precipitate, which discourages slippage of the plates. Temperatures for aging aluminum 6061 are relatively low, usually between 160 and 175 °C. Extrusions and forgings are held at the high end of the range for 8 h, with other product types being held at the lower temperature range for 18 h.

9.3.5 Welding

9.3.5.1 Austenitic stainless steel

Austenitic stainless steels are readily weldable by most processes. Major weld-design considerations include cleaning of weld surfaces, minimizing residual stress (leads to distortion, cracking, or both) with appropriate choice of fitup and heat input, appropriate choice of filler metal (usually type ER308L for 304L and ER316L for 316L) to provide a slightly ferritic weld to avoid hot cracking and inhibit carbide precipitation, and adjusting heat input to minimize precipitation in the heat-affected zone of the weld.

9.3.5.2 Carbon steel

The low-carbon steels can be easily welded or brazed by a number of conventional electric or gas methods if the impurity levels are kept low. Welding of lower grades or free-machining grades should be performed only when the finished components will be in the stress-free state. Although no thermal pretreatment of the weld area is normally required, the area should be free of oxide, dirt, and grease. Brazing using fluxes and copper alloy filler materials is easily accomplished with low-carbon steels. An intermediate temperature stress relief operation may be required after welding on complex geometries or if uncertainty exists about the in-service stress state of the component. If postwelding heat-stress relief is planned, the weld area should be thoroughly cleaned before heating.

The medium-carbon steels can also be readily welded and brazed if care is taken in designing and preparing the weld. Typically, the materials to be welded should be similar in composition and should be normalized or annealed before welding. Because these materials are frequently used for their hardenability, care must be taken to avoid quenching the weld area. Hardening in the weld area will be accompanied by a ductility loss which can lead to cracking or other forms of failure. Because any large mass adjacent to the weld can act as a sufficient heat sink to quench the weld, the components should be preheated before welding. Gas or electric arc welding with fluxes can produce good welds. Inert gas shielded arc welding may be used to avoid scale formation, but it is more expensive. Resistance welding is more difficult because of the high local heat and the propensity for cracking in the area adjacent to the weld. Brazing with copper alloys and fluxes is common and can be performed on these materials in either the hardened, tempered, or normalized state. After welding, the heat-affected zone surrounding the weld area may require stress relief or tempering, especially if this area will be stressed when placed in service. If care is used to eliminate all stress risers in the design of a weld, welded components can be hardened and tempered as a unit. However, this task usually requires a localized stress relief around the weld area that can be accomplished with a flame or heat tape or blanket. Before any postwelding heat treatment, the entire area should be thoroughly degreased and descaled.

9.3.5.3 High-strength steel

These steels are referred to as heat-treatable low-alloy (HTLA) steels. Because of their susceptibility to hydrogen-assisted cracking, these steels are generally welded in the annealed or overtempered condition, and the entire weldment is then heat treated to the desired strength or hardness level. These steels can be readily joined using the shielded metal arc and gas shielded arc welding processes if a minimum preheat and interpass temperature, to prevent cracking, is maintained and low-hydrogen procedures are employed. The preheat and interpass temperature is dependent on alloy content, heat-treatment condition, availability of hydrogen, joint thickness, and restraint. Care must be given during postweld heat treatment. In some alloys, the weld must not be cooled to room temperature until after it is given a thermal treatment to avoid cracking. These alloys can be brazed using processes, procedures, and filler metals commonly used for carbon steels. When the steel is to be quenched and tempered, brazing and hardening operations can be combined.^[12]

9.3.5.4 Aluminum alloy 6061

Good weldability is an important characteristic of Aluminum 6061. This alloy is generally readily weldable by all of the usual welding processes. However, some consideration must be given to the special qualities of the alloy. It readily forms an oxide that must be removed by flux, mechanical, or chemical means or avoided by welding in an inert atmosphere. Also, aluminum does not undergo any color change at welding temperatures, causing difficulty in judging when the metal is close to its melting point. Finally, its high thermal conductivity and electrical conductivity impose special requirements for fusion and resistance welding, respectively. Inert gas shielded arc is recommended because flux is not necessary. Resistance welding using special equipment is satisfactory. The strength of heat-treated alloys drops to a level comparable to that of nonheat-treated alloys in the vicinity of the weld. In all cases, the parts must be re-aged. When distortion will allow, solution treating and aging will provide maximum properties.

9.3.6 Bolting

9.3.6.1 Austenitic stainless steel

Galling (sticking together of mated/sliding metal surfaces) is a typical problem encountered in the bolting of Types 304L and 316L stainless steel components with traditional threaded bolt-and-nut components of matching composition. Galling can be mitigated with appropriate lubricants or with material selection. An example of the latter is choosing Type 304L stainless steel bolts with Type 303 steel nuts. Type 303 steel is very similar to Type 304L, except it is intentionally alloyed with small amounts of carbon, phosphorus, and sulfur to make it somewhat brittle on a microscopic scale; therefore, its surface tends to crumble during motion, thereby preventing sticking. In any case, bolting of Types 304L and 316L steel components should be performed with materials as similar as possible in composition to the primary alloy to avoid galvanic corrosion. A discussion of galling of threaded components can be found in the literature.^[13]

9.3.6.2 Carbon steel

Many grades of steel bolts are used for fastening plain carbon steel. Depending on their strength levels, bolts should be slowly torqued to avoid impact loading. A lubricant or rust chaser should be used to minimize galling and corrosion. Avoid the use of dissimilar metal bolting material (i.e., stainless steel).

9.3.6.3 High-strength steel

Many of these steels are used to make bolts and other fasteners. Because these materials are susceptible to stress corrosion in the hardened condition, use fasteners of the same (or very similar) alloy. Threaded fasteners fabricated with very high-strength materials ($S_u > 170$ ksi) may be particularly susceptible to stress corrosion cracking, especially when subjected to high preloading. High strength alloys which cannot be completely through-hardened (such as AISI 4140) should not be used for large diameter fasteners.

9.3.6.4 Aluminum alloy 6061

Mechanical joining of aluminum by fasteners poses no real technical problems. Generally, rivets are selected from a material to closely match the properties of the material to be joined. For bolts or rivets, some consideration must be given to coating the fastener to prevent galvanic corrosion of the part. Some form of plating, such as nickel, zinc, or cadmium, is typically used, depending on the environment in which the part is to be used.

9.3.6.5 Fir plywood

Plywood can be fastened to itself by nails, screws, and bolts. When using bolts, care must be exercised in making the bolt holes. If the hole is too large, the stress will be distributed nonuniformly. If the hole is too small, inserting the bolt can split the wood. With the other fasteners, the holding strength may degrade with time. This degradation may occur rapidly if the wood is subjected to periods of alternating high and low humidity.

9.3.6.6 Redwood

Redwood can be fastened with nails, screws, spikes, staples, or bolts. When using bolts, care must be exercised in making the bolt holes. If the hole is too large, the stress will be distributed nonuniformly, and inserting the bolt in to a hole that is too small can cause the wood to split. Holding strength may degrade with time when using other fasteners. This degradation may occur rapidly if the wood is subjected to periods of alternating high and low humidity.

9.3.7 Bonding

9.3.7.1 Insulating board (cellulosic fiber)

Insulating board components can be joined as desired by adhesive bonding to form the required assembly configuration. Most common construction adhesives curing at room temperature will produce a bond line of adequate strength to force failure of the insulating board. Epoxy adhesives may be used when service temperatures for the bond line approach the decomposition temperature of the board itself.

9.3.7.2 Ceramic fiber material

A number of adhesives and cements, both organic and inorganic, are available for bonding ceramic fiber materials. The manufacturer or supplier should be consulted for any particular application.

9.3.7.3 Fir plywood

Adhesive bonding can be used to supplement assembly of plywood to either itself or heavier wood members with nails or other fasteners to provide better stress distribution over the joint area. Through proper selection and use of an adhesive, an efficient and rigid adhesive-bonded joint can be as strong as or stronger than the wood itself, so some applications may not require additional fastening; therefore, plywood should be selected with few unrepaired defects and with a rough sanded face. Use of surfacing techniques that damage the wood structure can lead to premature bondline failure. Plywood with the appropriate texture for bonding should be purchased. Glued joints should not be designed primarily to transmit load in tension normal to the plane of the plywood sheet because of the low radial and tangential tensile strength of wood. Glued joints should be arranged to transmit loads through shear planes that are parallel to each other. Sufficient area must be provided between the plywood and the flange member of box beams and the plywood and the stringers of stressed skin construction to avoid shear failure perpendicular to the grain in the face veneer, in the adjacent ply, or in the wood member itself because shear strength across the grain is less than it is parallel to the grain. Enough pressure should be uniformly applied to the bond joint to distribute the adhesive evenly and to keep the adherents in intimate contact. Care must be taken to ensure the wood is not damaged while applying pressure. Best service in wood joints is achieved if the wood is bonded at a moisture content as close to that anticipated in the joint in service as is possible to minimize the tendency for the joint to separate because of dimensional changes.

Phenol formaldehyde and urea formaldehyde adhesives are two-part thermosetting systems and are typically heat cured. They can be formulated for room-temperature curing; however, room-temperature-curing phenolics are acid catalyzed and are not widely used because of potential damage to the wood. Room-temperature-cured urea adhesives have limited water and heat resistance and should be used only for interior applications. Resorcinol resins are also two-part systems that provide durable room-temperature-cured joints suitable for exterior and severe exposures. Two-part epoxy leads to a strong bondline but does not provide adequate moisture resistance. Epoxy can be used as a gap-filling adhesive because of the low shrinkage and low outgassing during cure. Aqueous emulsions of polyvinyl acetate are convenient, one-part, high-strength adhesives. They have limited resistance to moisture and can creep in joints under stress. Mastic adhesives can be used for thick and variable-thickness gluelines. They are usually solvent-based elastomers and do not provide much strength.

9.3.7.4 Redwood

Redwood generally bonds very easily using a wide variety of glues. The moisture content of the wood has much to do with the final strength of the bond and the dimensional stability of the glued members. However, redwood has a high dimensional stability, somewhat mitigating that consideration.

Also, if the wood has a moisture content of less than 12%, a satisfactory bond can generally be achieved. A wide range of products – animal, vegetable, natural and synthetic rubber products, and epoxies – are available to glue wood to wood. Good results can also be obtained by using some products to fill in chips or cracks in the wood.

9.3.7.5 Urethane foam

Foam structures are not generally bonded because of their highly porous surface. Compression fit is superior when possible.

9.3.7.6 Silicone foam

Foam structures are not generally bonded because of their highly porous surface. Compression fit is superior when possible.

9.3.7.7 Ethylene propylene elastomer

Bonding ethylene propylene elastomer with an adhesive can be performed, but the surface must be prepared with aggressive reagents and the resulting bonds are usually of low strength.

9.3.8 Plating

9.3.8.1 Austenitic stainless steel

Austenitic stainless steels can be plated to generate specific surface properties, but care must be exercised in achieving an intimate bond between stainless steel and the plating material. An oxide film forms on these alloys in many environments, including spontaneous formation in air, and this film interferes with bonding for many plating situations. Some aqueous baths can provide a surface appropriate for plating. Vacuum furnaces with hydrogen for reducing oxides followed by sputtering or vapor deposition is also a common method of plating stainless steel.

9.3.8.2 Carbon steel

Permanent protection of the low- and medium-carbon steels is neither cheap nor easy, but it can be accomplished if adequate care is taken in preparing the surfaces and if quality materials are used in the plating process. For a more or less decorative corrosion preventative, chromium plating is sometimes used, generally with a good undercoating of 0.05 mm of copper and 0.025 mm of nickel. Cadmium, tin, and zinc can all be applied. Metal-sprayed coatings such as zinc and aluminum are sometimes used for protection. These coatings require dry blasting of the surface before coating and sealing by wire brush and chemical treatment immediately after spraying. The most common form of protection for these materials is galvanizing, which involves dipping a chemically cleaned steel part into a bath of molten zinc under controlled time and temperature conditions that cause the zinc and the steel to react, forming a very adherent layer of zinc-iron compounds with free zinc at the surface. The layer of free zinc provides some barrier protection for the substrate and sacrificial corrosion protection when adequate moisture is available. Precautions for galvanizing are mainly related to potential for dimensional instability during rapid temperature changes. Galvanizing (or other coating and plating) should be performed after all forming and welding operations as the coatings can be damaged by deformation or heat and the coated components embrittled by welding. Stress relieving after plating of carbon steels may be required to prevent hydrogen embrittlement.

9.3.8.3 High-strength steel

Decorative chromium plating is not often required on these steels. When necessary, at least 0.05 mm of nickel or copper and nickel undercoat should be deposited below the thin coat of chromium. Cadmium and zinc plating 0.025 mm thick gives excellent corrosion protection under all normal conditions. The majority of these steels will be above 1000 MPa (145 ksi) tensile strength and require stress relieving at 200 °C after plating. If considerable machining stress exists, stress relief before plating is recommended. This task is required to eliminate hydrogen embrittlement, which can cause brittle failure below the calculated tensile strength. This defect becomes more serious as the hardness increases. Although hydrogen embrittlement can be entirely removed by the 200 °C stress relief treatment, visual proof that this is always carried out on every part is impossible. Because brittle failure of high-tensile-steel parts can be disastrous, it is recommended that parts manufactured from alloys with 175 to 200 MPa tensile strength be purchased and closely controlled through an approved QA Program.

9.3.8.4 Aluminum alloy 6061

Aluminum 6061 can be plated if specific surface requirements demand it. The oxide layer on the aluminum must be removed to achieve good contact between the plating material and the aluminum.

9.3.9 Painting

9.3.9.1 Austenitic stainless steel

Austenitic stainless steels may be painted (for cosmetics or further corrosion protection), but adhesion is often poor unless the surface has been roughened to provide an anchor profile and unless the type of paint or coating is selected with adhesion to a passive film on stainless steel in mind.

9.3.9.2 Carbon steel

Painting plain carbon steel is a common method used to improve the cosmetic appearance and increase resistance to atmospheric corrosion. Any improvement in atmospheric corrosion resistance depends significantly on the quality of the paint or coating chosen (durability, permeation resistance, and ultraviolet light resistance) and the degree of surface preparation imparted to the steel. Before application of a paint or coating, the steel must be dry and free of any scale, grease and oil, and other debris. This task can be accomplished by chemical cleaning, grit blasting the surface, or both.

In addition, the steel must have an appropriate anchor profile (roughness) to hold the paint or coating. This goal can be accomplished chemically, but mechanical methods such as grit blasting are usually superior. The choice of paint or coating depends on the expected environment and desired service life. Because of the labor-intensive operations necessary for surface preparation, painting or coating the carbon steel may add significantly to the cost even above that of the paint or coating itself.

9.3.9.3 High-strength steel

When properly controlled, grit blasting is the best method for cleaning and preparing the surface of high-strength steel as it leaves a roughened surface to act as a key for the subsequent film. The surface must be brushed to remove the dust caused by blasting, and the subsequent treatment must be carried out as soon as possible after blasting because the freshly prepared surface can corrode very rapidly.

Phosphate treatment acts as an excellent paint base and is in itself a corrosion-resistant film and an oil-retentive surface. In this condition and if the oil film is maintained, long corrosion-free life can be achieved under indoor conditions. Steels above 1000 N/mm² tensile strength should be stress relieved to eliminate hydrogen embrittlement. The phosphated surface must be oven dried before application of zinc silicate or chromate primer. For best results, top coats of paint should be applied as quickly as possible after the primer.

9.3.9.4 Aluminum alloy 6061

Aluminum 6061 can be painted to enhance appearance or for further corrosion protection if desired. Many of the considerations of bonding apply to painting aluminum surfaces. For high-finish surfaces, roughening with a metal brush or chemical etching is generally required to improve paint adhesion. Best paint performance can be obtained with epoxy-polyamide paints on an anodized surface.

9.3.9.5 Insulating board (cellulosic fiber)

Insulating board can be painted for reduction of dust or handling damage, for identification, and for flame-retardation.

9.3.9.6 Ceramic fiber material

Ceramic fiber materials can be painted for identification.

9.3.9.7 Fir plywood

Plywood intended for continuous outside exposure should be protected from ultraviolet degradation. Plywood can be finished with water-repellent preservatives, stains, or house paint. Water-repellent preservatives are formulated to penetrate the wood surface and are used if the natural finish is to be retained. Shellac or varnish will tend to crack or peel because they do not penetrate the wood. Acrylic latex, oil-based, or solvent-based stains provide adequate weathering protection. Acrylic latex paint is recommended and should be used with a primer and a top coat. Fir plywood must be sealed with either shellac or a special fir-plywood primer before painting. Do not use oil or alkyd paints because they tend to flake. Prefinished plywood and plywood treated for protection against fire or decay can be purchased. Plywood is usually treated after the plies are glued so that only panels made with exterior glue are treated. Wood preservation techniques for plywood are the same as for ordinary lumber.

9.3.9.8 Redwood

Paints or other finishes, such as varnishes and water repellents, can be applied readily to redwood. Such finishes can be used for cosmetic reasons or to protect the wood. Moisture content of the wood should be low, preferably less than 12%. Applying paint or another finish to redwood is usually straightforward. Consideration should be given to the environment in which the wood will be placed. If the environment is wet or at an extremely high level of humidity, a water repellent should be used as a first step, then a primer and the final finish can be applied. Best results are obtained by using two to three coats of varnish, lacquer, or paint. However, because redwood has a high natural resistance to decay, acceptable results can be obtained with fewer coats.

9.4 MATERIAL QUALITY

9.4.1 Austenitic Stainless Steel

The composition and properties of austenitic stainless steel are controlled by a number of ASTM specifications. Perhaps the most significant composition feature is the carbon content, which separates the "L"-grade material (0.030 or 0.035% carbon maximum, depending on allowances for product form and analysis details) from the standard grade (up to 0.08% carbon allowed). Other elements are controlled within specific ranges or with maximums, and experience shows that meeting all of the composition requirements for these materials is both technically significant and relatively easy for vendors. Deviations from the composition requirements should not be lightly regarded.

Some specifications also include requirements for mechanical properties (usually minimum strength or ductility, maximum hardness), heat treatment (usually solution treatment or annealing), or other requirements for fabrication. In addition, each specification usually contains a list of other applicable specifications that are useful to or invoked by the procurer of the material. It is beyond the scope of this document to list every applicable specification (ASTM or other organizations); however, depending on product form and the other requirements desired by the customer, several common ASTM specifications for these alloys include the following:

- *ASTM A240: Standard Specification for Heat Resisting Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels*
- *ASTM A276: Standard Specification for Stainless and Heat-Resisting Bars and Shapes*
- *ASTM A484: General Requirements for Stainless/Heat-Resisting Bars, Billets, and Forgings*
- *ASTM A666: Standard Specification for Austenitic Stainless Steel Sheet, Strip, Plate, and Bar*
- *ASTM A743: Standard Specification for Castings, Iron-Chromium, Iron-Chromium-Nickel, Corrosion Resistant, for General Application*
- *ASTM A744: Standard Specification for Castings, Iron-Chromium-Nickel, for Severe Service*

A common corrosion test specification used for austenitic stainless steels is ASTM A262 (*Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels*). This specification contains a number of recommended practices for conducting standardized corrosion tests. Experience shows that requirement of passing Practice A (oxalic acid etch) and Practice C (boiling nitric acid test, limit 0.020 in. per month average in at least three test periods) for each heat or lot results in quality material with maximum corrosion performance characteristics. This test is most common for "L"-grade materials in service where corrosion resistance is typically very important, and it is a restrictive requirement in that many vendors do not have immediate access to this data for the materials on hand. Therefore, testing at an independent laboratory is required, which increases costs and adds time to the procurement schedule. However, the requirements of the corrosion tests are not overly demanding, and quality material should pass these

tests without deviation. For very mild service conditions, these tests are sometimes waived or minimized (e.g., requiring only Practice A). The necessity of this requirement (or others imposed by the various ASTM specifications) must be judged for each application, and it is recommended that input from an individual experienced in these tests be obtained for each procurement.

9.4.2 Carbon Steel

The quality of the carbon steels can be roughly assessed from the phosphorus and sulfur contents, which should be as low as possible unless specifically added to aid machinability. Any other residual elements present could have an adverse effect on welding because they tend to increase hardenability. The AISI/SAE designation and standard practices used to describe plain carbon steel are not specifications and contain only a portion of the information (namely range of chemical composition) needed to properly describe a plain carbon steel product for procurement. ASTM publishes the most widely used standard specifications for procuring plain carbon steels; they are fairly complete and are generally oriented toward performance of the fabricated end product. Most ASTM specifications for bars, wires, billets, and forgings and some specifications for sheet products incorporate the AISI/SAE designations indicating chemical composition. However, the specifications for plate and structural shapes usually specify the limits and ranges of chemical composition directly without using the AISI/SAE designation. Some of the commonly used ASTM specifications for procuring carbon steels are as follows:

- *A108: Standard-quality, cold-finished carbon steel bars*
- *A576: Special-quality, hot-rolled carbon steel bars*
- *A611: A, B, C, or E Grade Cold Rolled Structural Quality (0.2% carbon, 0.6% manganese)*
- *A659: Commercial-quality, hot-rolled carbon steel sheet and strip*

The Aerospace Materials Specifications (AMS) published by SAE are also complete specifications that can be used for procurement; however, because these specifications pertain to materials used in the aerospace industry, they may contain unnecessarily strict specifications on such things as mechanical properties. These specifications may require special processing methods that will cost more than steels of similar composition intended for other applications. An exhaustive list of ASTM, AMS, and other specifications is given in the literature.^[2]

9.4.3 High-Strength Steel

A variety of forms, grades, and classes of high-strength, low-alloy, medium-carbon steels are available commercially. Many of these materials are used in the aerospace industry. Hence, many specifications have been developed by the government (Military Specifications) or by other groups, such as the Aerospace Materials Specifications published by the SAE, Inc., that are suitable for use in procuring these materials. Some of these are written for specific uses; others refer to specific forms. Still others are more general in nature and may not be sufficient for procurement without additional information. Some specifications call out the alloy manufacturing process, which may have an indirect effect on the physical or chemical properties of the materials. Because AISI 4340 is considered a standard for medium-carbon, low-alloy, high-strength steels, sample specifications appropriate for procuring this material are as follows:

- *AMS 6359: Steel, Sheet, Strip, and Plate (0.8 Cr - 1.8Ni - 0.2SMo 0.38-0.43C) (SAE 4340)*
- *Mil-S-5000: Steel Chrome-Nickel-Molybdenum (E4340) Bars and Reforging Stock*
- *Mil-S-8844: Steel Bars, Reforging Stock, and Mechanical Tubing, Low Alloy, Premium Quality*

Most specifications reference other standards or specifications for measuring properties, determining composition, detecting flaws, etc.

9.4.4 Aluminum Alloy 6061

The systems for designating alloys and tempers are covered by national standard ANSI H35.1-1982. The rules by which alloy distinctions are also made and designations assigned are a part of this document. Aluminum association composition limits for wrought aluminum alloys provide a chemical purity standard. Because the principal use of this alloy has been heavy-duty structures requiring good corrosion resistance (e.g., aircraft, railroad cars, pipelines, marine craft, etc.) this alloy is sold to consistently high standards. Specifications from the aerospace industry will provide for maximum control.

9.4.5 Insulating Board (Cellulosic Fiber)

A variety of standard sizes and grades of insulating board are available from manufacturers of wood-based products. Examples of board grades available include roof insulating, sheathing, building, shinglebacker, and sound deadening. Sizes (width and length) vary from 1 ft by 1 ft to 4 ft by 12 ft, and thicknesses vary from 1/2 to 3 in. when manufactured in accordance with ASTM C208, specification for commercial products. More restrictive specifications do not exist.

Standard specifications and methods of testing for insulating board products include the following:

- *ASTM C165: Measuring Compressive Properties of Thermal Insulations*
- *ASTM C208: Standard Specification for Insulating Board (Cellulosic Fiber), Structural and Decorative*
- *ASTM C209: Standard Method of Testing for Insulating Board (Cellulosic Fiber), Structural and Decorative*
- *ASTM D1554: Definition of Terms Relating to Wood-Base Fiber and Particle Panel Materials*
- *ASTM D2277: Specification for Fiberboard Nail-Base Sheathing*

9.4.6 Inorganic Refractory

Several ASTM standards are applicable to inorganic refractory materials. For the application of these materials as impact absorbing and thermal insulating materials for Type B packages the most important ASTM standards are modulus of rupture (ASTM C 133), permanent linear change (shrinkage) (ASTM C 113) and thermal conductivity (ASTM C 417).

9.4.7 Ceramic Fiber Material

The ceramic fiber materials industry in general does not provide uniform commercial specifications. However, the rigorous conditions under which these materials are normally used have required that the vendors provide reliable physical and mechanical property data. The reference listed for this material^[7], ASTM standards, and vendor literature provide the best basis for specification preparation.

9.4.8 Fir Plywood

Several ASTM standards concern the measurement of flexural (D3034), tensile (D3500), compressive (D3501), shear strength (D2718), shear modulus (D3044), and toughness (D3499). ASTM D1038 lists standard definitions used in relation to plywood. The quality of the plywood will depend on the adhesive used and the source of the wood. The APA-adopted PS1 standard governs the production and grading of plywood.^[8] The standard includes specifications concerning the requirements for species, grade, thickness of veneers and panels, glue bonds, moisture content, standard definitions of terminology, suitability, and performance test specifications. The stamp on plywood indicates the standard; not all APA plywood conforms to the PS1 standard. APA performance-rated grades and a Federal Housing Association standard exist. Not all imported plywood follows the PS1 standard, and those that do will not carry the APA stamp. The stamp also lists a mill number that indicates the manufacturer of the plywood; this number can be useful if an exact match to existing stock is desired.

9.4.9 Redwood

Redwood stock from the heartwood is moderately light in weight while possessing moderate strength stiffness and hardness. The heartwood has high decay resistance, is easily worked, is straight grained, and shrinks and swells comparatively little. In addition to normal lumber specifications, the purchaser should avoid pieces containing the sapwood, which is almost white in contrast to the light cherry to dark mahogany heartwood. The wood splits readily, and structural pieces should be selected with an eye toward avoiding stress points or flaws that can initiate splits.

9.4.10 Urethane Foam

Most urethane foams produced on the continuous production lines are uniform and easily sampled randomly for properties. Vendor certification of properties measured for their high-volume customers are readily available. Prepackaged "foam in place" kits are more difficult to use especially when it is necessary for the final product to have specific uniform properties. Vendor instructions must be followed exactly, temperature and humidity limits observed, component shelf life honored, and extreme cleanliness maintained to achieve uniform properties. Most kits are not intended for applications where predictable compression set and strength or high-temperature stability are essential.

9.4.11 Silicone Foam

Most silicone foams produced on proprietary production lines are amazingly uniform and easily sampled randomly for properties. Vendor certification of properties measured for their high-volume customers are readily available. Prepackaged "foam in place" kits are more difficult to use in obtaining uniform properties. Vendor instructions must be followed exactly, temperature and humidity limits observed, component shelf life honored, and extreme cleanliness maintained to achieve uniform properties. Most kits are not intended for applications where predictable compression set and strength or high-temperature stability are essential.

9.4.12 Ethylene Propylene Elastomer

The O-ring manufacturer needs to know the O-ring's required inside diameter, cross-sectional diameter, shape, and the material formulation. The manufacturer must provide product batch and lot identification that will allow complete traceability at virtually any time during its life cycle. The manufacturer's internal Quality Assurance system should allow for the retrieval of data on the physical properties of any given lot of product from compounding to finished product. Actual lot values of hardness, tensile strength, ultimate elongation, and specific gravity are a minimum.

Determining physical properties of elastomers, whether required for quality control, compliance with specifications, or research and development, is a challenge. Tests used for other solid materials are seldom applicable to elastomers. Ultrahigh deformations and low moduli of elastomers require test equipment to be accurate at higher displacements and lower forces than are needed for most other engineering materials. Good reproducibility can be obtained only from thoroughly developed methods, which is one of the reasons for the many standardized tests used for elastomers. Reproducibility of results, especially between laboratories, is very poor for elastomers unless the standards are carefully followed. Equal attention to detail is required in interpretation of test results.

The elastomers are evaluated by the as-cured physical properties (ASTM D 412 and D 1414), aged physical properties (ASTM D 573), compression set (ASTM D 395), and fluid aging (ASTM D 471). Low-temperature properties tested are low-temperature retraction TR10 (ASTM D 1329), torsional or dynamic modulus (ASTM D 1053), and brittle point (ASTM D 746). Occasionally, special tests may be required, depending on the application. Some examples are tear resistance (ASTM D 624), electrical strength (ASTM D 149), dielectric constant and dissipation factor (ASTM D 150), and volume resistivity (ASTM D 257).

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